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Utilisation of Agricultural and Food Waste for Biofuel Production: A Pathway to Sustainable Energy Transition

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Abstract: The global rise in population and industrial activities has led to an increased reliance on petroleum-based fuels, resulting in significant environmental concerns, including the intensification of emissions and global warming. Concurrently, the agricultural and food processing sectors generate substantial amounts of organic waste, which, if inadequately managed, can contribute to environmental degradation. However, extensive research over recent decades has demonstrated that such organic waste can be converted into biofuels through appropriate treatment processes. In light of the growing need for sustainable energy solutions, global efforts have been increasingly focused on the exploration of renewable resources for power and electricity generation. This review aims to explore the potential role of agricultural and food wastes as feedstocks in the production of biofuels and chemical products, which can serve as substitutes for petroleum-based products. The review synthesises recent findings from multiple disciplines, including agriculture, food science, and energy, by analysing publications in leading academic databases such as Scopus, ScienceDirect, and Web of Science. These studies focus on the global production of agricultural and food wastes, their energy potential, and their contributions to the energy transition, with particular emphasis on biofuels such as biomethane, biohydrogen, bioethanol, and jet biofuel. The findings indicate that the conversion of organic waste into biofuels offers a viable solution for reducing pollution, managing waste, and promoting a circular economy. Furthermore, it presents significant opportunities for advancing sustainable energy production. The review concludes by highlighting the key challenges and knowledge gaps that must be addressed in future research to maximise the potential of these waste-to-energy technologies.

Keywords: Energy production; Renewable energy; Biofuels; Agriculture wastes; Food wastes; Sustainable energy transition

1 Introduction

The continuously increasing need for energy and food to attend to the growing global population and the worldwide expansion of industrial activities, besides the global recommendation to avoid greenhouse emissions, urged the adoption of renewable energy sources and eco-friendly fuels. In this context, agricultural products, agricultural and food wastes (FWs), and other animal wastes such as fats, etc. appear as viable options for diversified energy production besides the recovery of minerals and chemical elements essential for industrial activities. Agriculture contributes to greenhouse gas by about 19.9% and generates big amounts of organic waste, which, when treated inadequately, decomposes and contributes significantly to greenhouse emissions.

Driven by these needs, many research activities and developments were devoted to evaluating the potential of agriculture and FWs for producing biofuels and chemical products. A big variety of agricultural wastes were examined, and their physical, chemical, and thermal properties were determined to be able to choose the appropriate methods for their treatment for energy conversion and extraction of chemical products.

Sugarcane is used to produce sugar and ethanol, while the bagasse is used for electricity and heat. Bagasse is being investigated as a raw material for producing second-generation (2G) ethanol. Similar agricultural products such as corn, wheat, cassava, and sugar beets were investigated to use their wastes as raw material to be transformed into a variety of fuels and products. The processes used to convert the agricultural wastes to biofuel include thermochemical, where the biomass is converted by gasification and pyrolysis, while the biochemical processes convert the biomass by fermentation of carbohydrates.

The objective of this investigation is to demonstrate the suitability of agriculture and FWs for producing biofuels and chemical products normally obtained from petroleum. To achieve the objective, an extensive literature review was done in different related areas such as food, agriculture, fuels, and energy, with a focus on the production of biofuels and energy transition. This wide coverage, the focus on organic wastes to produce biofuels for energy transition, and the inclusion of future research trends and opportunities are what distinguish the present review from previous ones. As a contribution, the present review shows the potential of agro- and food-wastes as feedstock to produce biofuels, strengthens the circular economy, and enhances the energy transition.

The contents of the review are 1. Introduction; 2. Agriculture and Food Wastes; 2.1 Generalities; 2.2 Biofuels; 2.3 Biofuel Production Methods; 3. Gaseous biofuels from Agriculture and Food Wastes; 3.1 Biogas; 3.2 Biomethane; 3.3 Biohydrogen; 4. Liquid Biofuels from Organic Wastes; 4.1 Bioethanol; 4.2 Biodiesel; 4.3 Jet Biofuel; 5. Solid Biofuels from Organic Wastes; 6. Biorefinery and Biofuels; 7. Conclusions and Future Research Opportunities; Nomenclature; References. Relevant remarks are given after each section.

2 Agriculture and Food Wastes (FW)

2.1 Generalities

Agricultural waste refers to unwanted plant residues from crop cultivation, such as stems, leaves, and pruning, processing of agricultural products, and animal farming operations. FW is food that is discarded within the supply chain, from the farm to the consumer, due to damage, spoilage, or being uneaten.

The expansion of agricultural production increases the volume of agricultural waste and is estimated at about 998 million tons yearly. The organic part generated from municipal solid waste (MSW) is usually about 44%. The UN Environmental Program predicts the increase of MSW from 2.3 to 3.8 billion tons in the period 2023–2050 [1].

Global food and agricultural waste in 2023 reached about 1.3 billion tons, or approximately 30% of the global food production. These losses cause a financial loss estimated as $940 billion to $1 trillion per year, besides contributing 8–10% to global greenhouse gas (GHG) emissions, loss of biodiversity, and inefficient use of resources. These projections alert about the need to improve the management and conversion of organic wastes to biofuels, biofertilizer, energy, and other materials of industrial use [2, 3].

About 80% of a plant is considered agricultural waste, which includes stems, leaves, and branches. According to the report [4], globally about 1.2 billion tons of food are wasted on the farm, which represents a loss of approximately 15.3% of food produced globally at the farming stage.

Agriculture and FWs are usually rich in sugars, starch, and other chemical compounds, which make them adequate candidates for the production of biofuels such as biogas, bioethanol, biodiesel, and others by using biochemical and thermochemical processes.

2.2 Biofuels

Biofuels are produced from biomass, including agricultural crops, forestry residues, livestock manure, and the organic fraction of MSW, by a variety of available technological routes. The four generations of biofuels are identified according to the raw material and the production technique. Edible crops are used to produce first-generation (1G) biofuels, where bioethanol is produced from corn, sugar beet, and sugarcane, while biodiesel comes from soybeans and vegetable oils. The production of these biofuels on a big scale poses serious problems relative to food supply and security besides land use.

Research results indicated that agriculture and FWs can be used as input for producing biofuels besides resolving the problem of organic waste management. Organic wastes are used to produce 2G biofuels, where bioethanol is produced from lignocellulosic agricultural residues and biodiesel from used oil, fats, etc.

The third-generation (3G) of biofuels focuses on utilizing algae as a raw material, offering high oil yields and minimal land use. Algae-based biofuels are considered a promising route for producing sustainable biofuels, but challenges in harvesting, processing, and scaling up production persist. Fourth-generation (4G) biofuels involve genetic engineering of microorganisms and process design to optimize biofuel production. The generations 3G and 4G are still under development [5, 6].

In 2023, global biofuel daily production achieved 960,000 barrels of oil equivalent, compared to daily production of 12,000 barrels in 2000. Global ethanol production in 2023 reached 116 billion liters, while global biodiesel production was around 50 billion liters. Government policies, incentives, and ambient impacts of global warming enhanced biofuel production [7].

Biodiesel is less stable, and light, temperature, and humidity increase its deterioration. Also, it has increased emission of NO_x, which generates acid rain. Drawbacks of biofuel production and use include land and water requirements and air and groundwater pollution [8].

The biomass production capacity and the high sugar and fiber content made sugarcane a potential feedstock for bioethanol, while the conversion of its bagasse to 2G ethanol helps to meet future fuel demands [9].

To convert organic wastes to biofuels, there are a variety of available methods, such as fermentation and anaerobic digestion, and others are in the final development stage, such as dark fermentation and photo fermentation.

2.3 Biofuels Production Methods

Thermochemical and biochemical processes are among the methods used to convert agricultural and FW into biofuels (Figure 1). Thermochemical methods include pyrolysis, gasification, and torrefaction. The pyrolysis of the biomass needs heating without oxygen to produce bio-oil, syngas, biochar, and biocoal, while gasification needs heating with a controlled oxygen supply to produce syngas. Torrefaction involves heating the biomass in an oxygen-free ambient at temperatures between 200 and 300°C to produce a solid fuel with improved energy content and enhanced combustion properties [10, 11].

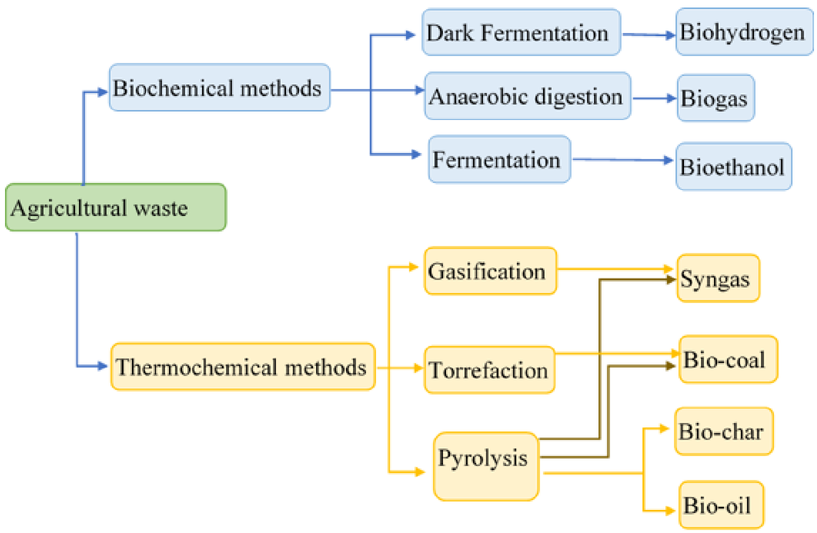

Figure 1. Methods for biofuels production from agricultural waste, adapted from the study [12]

Biochemical methods include anaerobic digestion, fermentation, and dark fermentation, besides other methods. In the anaerobic digestion, the organic material is converted by microorganisms, producing biogas, while fermentation converts sugars and starches into bioalcohols like ethanol. In the case of dark fermentation, the microorganisms convert organic substrates into biohydrogen. Although being a promising technology, it is still under development for hydrogen production. The process can easily be integrated with waste/wastewater treatment and has a lower cost compared to other methods [10–12].

Remarks

Food quantity and quality are among the most important pillars for the survival of humans. In regular agriculture activities involving plantation, harvesting, transport, and distribution, many losses occur, and part of the production never reaches the consumer. These organic wastes, if not treated correctly, can degrade and produce greenhouse gases, which impact the environment, producing global warming and causing climatic changes, and can generate up to 10% of the global GHG emissions. Globally, the production of 1G biofuels threatens food security and interferes with water and land use. These concerns enhanced the search for other alternative eco-friendly raw materials. Organic wastes (from agriculture and food industries, residential and commercial sectors), such as lignocellulosic biomass, used oil, fats, etc., are adequate for producing 2G biofuels and chemical products, which can enhance the circular economy and create jobs. Both 3G and 4G biofuels are still under development with promising results. Challenges include more research and investments, besides adequate regulations and public policies to put them in conditions to compete in the fuel market.

3 Gaseous Biofuels from Agriculture and Food Wastes

Globally, huge amounts of organic waste are annually generated and must be treated adequately to avoid ambient contamination and production of GHGs. Summed up with the emission produced from fossil fuels, about 21.3 billion tons of CO_2 are annually released into the atmosphere, causing global warming impacts. Hence, to restore the quality of the environment and reduce aggressions on its integrity, it is necessary to reduce fossil energy use and adequately treat organic wastes [7].

Agriculture waste (AGW) refers to the unused part of the plant crop and accounts for about 80% of the plant. Globally, agriculture generates a substantial amount of waste, estimated between 1.3 and 2.1 billion tons annually, which highlights their abundance and availability for conversion into valuable products for various industrial sectors. By adopting sustainable waste management practices, the agricultural sector can minimize its environmental footprint, enhance the circular economy, and help to give a correct destination to large volumes of organic matter and at the same time provide ambient sound fuels [13–15].

3.1 Biogas

Biogas is generated by biodigestion of organic matter, producing mainly methane, carbon dioxide, and small amounts of other gases. Figure 2 shows the possible sources of feedstock used to generate biogas.

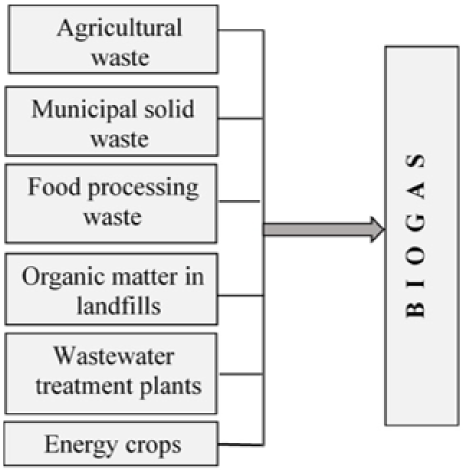

Figure 2. Organic wastes for biogas production, adapted from the review [16]

The recovery of energy and materials from these wastes avoids extraction of raw materials and natural resources and reduces emissions. Biogas generation from these wastes involves initially the decomposition of organic matter into acidic substances, which are subsequently consumed by the methanogenic bacteria to produce methane and CO_2. Biomethane is obtained from biogas by removing carbon dioxide and impurities. Biohydrogen produced from wastes is also being investigated and can be used in fuel cells, among other commercial applications.

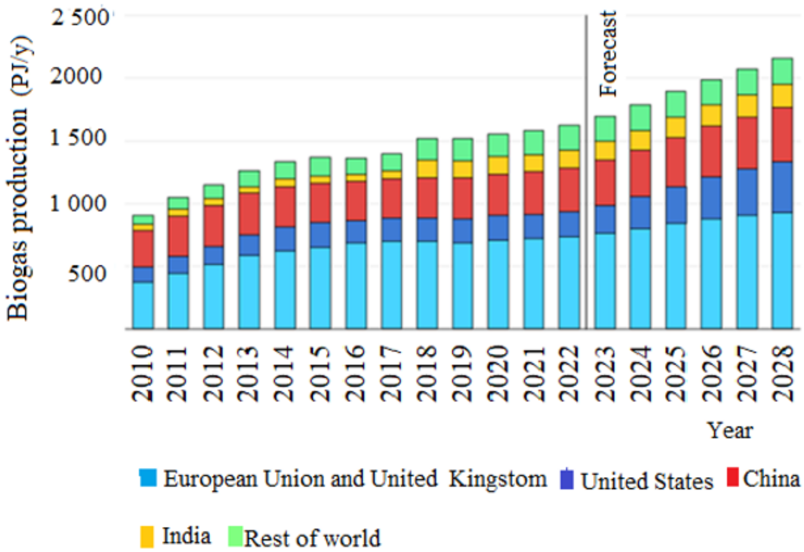

Figure 3. Global production and forecast of biogas from 2010 to 2028 [17]

Global biogas and biomethane production reached 22 billion cubic meters in 2023, according to the European Biogas Association. This volume is equivalent to 7% of the EU's natural gas consumption. International Energy Agency projects that global biomethane production could nearly double from 2023 levels by 2027 [17]. Figure 3 shows biogas global production and forecast in the period of 2010–2028, while Figure 4 shows a simplified line diagram of biogas production.

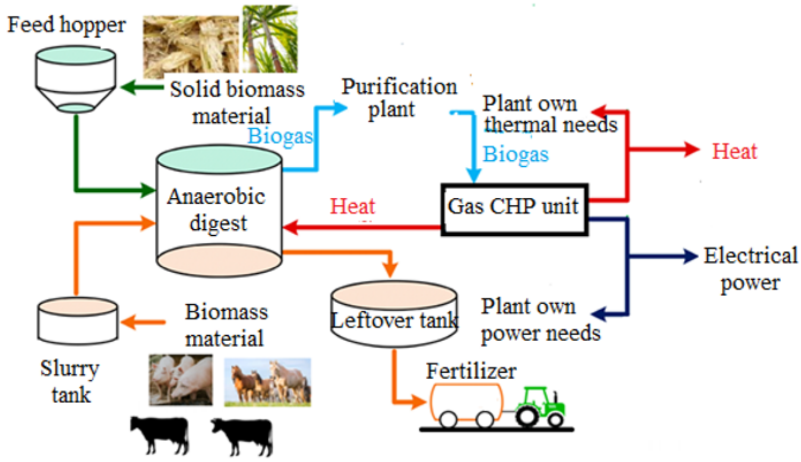

Figure 4. Simplified line diagram of biogas production plant, adapted from the study [18]

Investigations evaluated the ideal operational conditions, productivity, and possible applications, such as Caruso et al. [19], who reviewed the biological treatment of agriculture and food biomass residues with a focus on co-digestion and pre-treatments. The challenges included improving energy yields, reducing environmental impact, and increasing competitiveness. Mirmohamadsadeghi et al. [20] and Atelge et al. [21] reviewed FW as feedstock for producing biogas, the co-digestion for improving the biogas yield, and the process's recent developments. Future developments and challenges of biogas production from these wastes were also addressed. Kapoor et al. [22] examined the AGWs for producing biogas and extended its application for heat and electricity generation. The barriers and research opportunities were also addressed.

Upgrading biogas to produce biomethane also recently received intense attention due to the expanding market. Ardolino et al. [23] reviewed and compared the current methods to purify biogas to obtain biomethane from the biodigestion of the organic part of MSW. The results indicated that all the examined options were sustainable. Chavan et al. [24] reviewed the valorization of biomass residues from the industrial sectors. Adding value to the organic waste and producing products with the preferred characteristics is of great environmental and economic value. Saravanan et al. [25] reviewed the biological treatment technologies of organic wastes, including MSW, to generate biogas and biomethane and reduce the volume of discarded wastes. Alengebawy et al. [26] reviewed biogas production, agricultural wastes, and the applications of biogas.

Kumari et al. [27] reviewed FW and its conversion into biofuels and animal feed by using techniques such as pyrolysis, composting, anaerobic digestion, and hydrothermal carbonization. In their reviews, Egwuatu et al. [15] and Kapoor et al. [28] highlighted the transformation methods of organic wastes into bioenergy and discussed its environmental impacts. Jameel et al. [29] summarized the current and future perspectives of anaerobic digestion for biogas production and indicated the opportunities for process optimization.

Biogas from anaerobic digestion of organic wastes can help address global warming and improve waste management besides obtaining renewable energy. The use of co-digestion with microalgae integrated within the biorefinery concept is highly beneficial [30].

Attarde et al. [31] provided a review that discusses the potential of agricultural waste to be used for biofuel production. The review discusses various methods for generating energy from agricultural waste and the pretreatment methods used to enhance the conversion process. Challenges such as the moisture content and the processing costs were also addressed. Sarker et al. [32] presented a review of the sustainable techniques available to use waste for bioenergy production. Moreover, the physicochemical properties of various bioenergy products, including biogas, biochar, and bio-oil, were reviewed, and their possible applications were discussed.

Remarks

Global biogas production is continuously increasing, driven by growing demands and global warming impacts. Biogas contributes to decarbonization, waste management, and economic development. The future of the biogas industry is highly promising, with several energy developments, including integration with other energy systems to create hybrid systems. Furthermore, biogas presents a viable route for producing biomethane, a more powerful fuel that can substitute natural gas in domestic and commercial applications.

3.2 Biomethane

Biomethane is obtained from biogas by the removal of impurities like CO_2, H_2S, and water vapor. Co-digestion of mixtures of different organic materials is found to enhance biogas production. Generally, anaerobic digestion of organic wastes can produce 100–200 cubic meters of biogas per ton. Gasification of biomass is another method of producing biomethane, where the resulting synthesis gas (syngas) can be processed into methane or other fuels. Also, renewable-based electricity can be used to produce hydrogen, which can be combined with carbon dioxide to produce methane. Figure 5 shows the evolution of global biomethane production in the period 2010–2023. Figure 6 shows a simplified line diagram of the biogas and biomethane production from agricultural waste. Figure 7 shows the co-digestion of organic animal and vegetal wastes and the biogas and biomethane applications.

Figure 5. Evolution of global biomethane production [33]

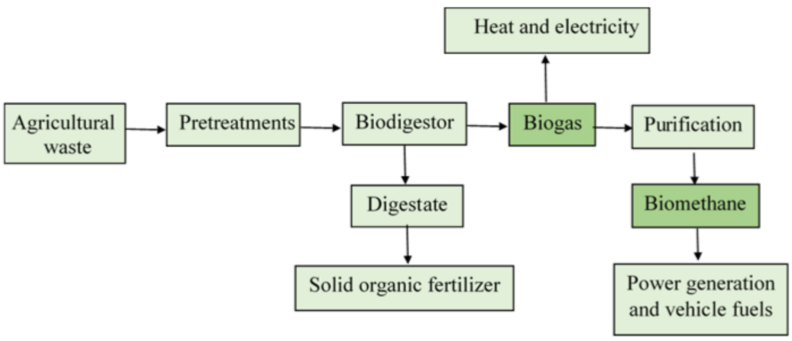

Figure 6. Diagram of biomethane production from agro-wastes, adapted from the study [34]

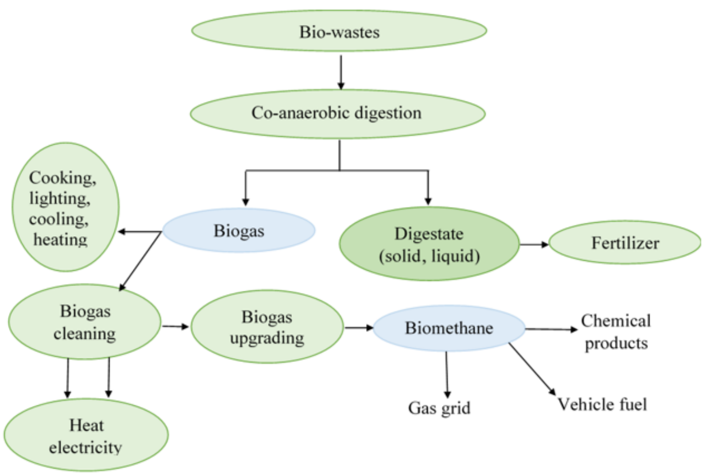

Figure 7. Applications of biogas and biomethane, adapted from the study [35]

Angelidaki et al. [36] presented a critical review on the upgrading techniques, biomethanation efficiency, current challenges, and the need for incentives. Chew et al. [37] reviewed the anaerobic digestion, influencing factors, and the effect of pre-treatments and co-substrates to increase biogas yield from FW. Khan et al. [38] commented on the limitations of the existing upgrading methods along with recent advances and possible future solutions, such as hybrid systems. Franco et al. [39] reviewed the life cycle of biomethane and pointed out the benefits achieved by using biomethane produced from waste. The barriers found include inadequate public policy, inadequate energy distribution networks, low government incentive, and high energy consumption. Assandri et al. [40] evaluated the utilization of agro-residues generated locally to produce biomethane to fuel the farm tractors and reduce the CO_2 emissions. The results confirmed the viability of the concept. Obaideen et al. [41] summarized challenges and barriers associated with biogas production, including increasing renewable energy, reducing climate change, enhancing the waste management process, and creating jobs.

Vijayakumar et al. [42], Awogbemi and Von Kallon [43], Keerthana et al. [44], and Sendilvadivelu et al. [45] presented reviews of the recent achievements and advances in technologies of biogas plants, biofuel production from agricultural wastes, pretreatment, production methods, and application. They also addressed the economical, technical, and other aspects affecting biogas production besides future research and developments.

Methane produced from landfills in Iraq was estimated in the interval 2023–2070. The results showed that the total amount of methane is 875,217 tons, sufficient to generate about 287,442 MW/year during the period [46]. Gallego-García et al. [47] reviewed the recent advances in pretreatment of lignocellulosic and food residues and discussed the barriers and challenges. Neri et al. [48] reviewed the influence of the substrate pretreatment and optimization of the operating parameters, which can increase biogas yield and production. The potential and barriers for using agro-FWs to produce biogas were also discussed.

Karne et al. [49] reviewed various available systems for upgrading biogas, including adsorption, scrubbing, and membrane technology, and commented on possible solutions to the obstacles of the different upgrading techniques and the economic viability of these systems. Mignogna et al. [50] highlighted modern trends and strategies for biogas and biomethane production and their potential as renewable sources. Aworanti et al. [51] provided a review of the intensification strategies to overcome anaerobic digestion challenges and enhance biogas production, purification, cleaning, and upgrading. Liang [52] and Akanji et al. [53] conducted investigations focused on the integration of different biogas production and upgrading methods to enhance biomethane system yield, performance, and economic sustainability. Supply of mixtures of food and organic wastes for the co-digestion process can increase the biogas productivity. Tadesse and Lee [54] examined the global landfill biogas consumption and reviewed its generation and utilization technologies and the possible social and economic gains and impacts.

Gontaruk et al. [55] analyzed the potential development of biogas and biomethane production, the contribution to the green economy, and the conversion of agricultural wastes into and discussed the potential uses of biofuels. Teoh et al. [56] reviewed different hydrothermal operations for biofuel production from different biomass. With hydrothermal processes, wet biomass can be directly utilized without drying. Agricultural and forest residues, energy crops, algae, sludge, litter, and FW can be utilized to produce biofuels. Begum et al. [57] highlighted the advancements and future of thermochemical and biochemical conversion processes for the production of green fuels, improving the circular economy and resource usage.

Sher et al. [58] reviewed the emerging technologies for biogas pretreatment, production, and upgrading processes and discussed the current and future perspectives of biogas. It was found that pretreatment technologies such as chemical, physical, thermochemical, and oxidative increase biomethane and biogas yield. Veeramuthu et al. [59] commented that techniques such as co-substrate dosing could increase the yield of biomethane. The findings focused on biomethane importance, the type of materials utilized, technologies in their production, and exploration of their application in transportation, electricity, and heat generation. Jepleting et al. [60] proposed new ways to improve the performance and the potential of low-cost biogas purification materials.

Remarks

Global biomethane production reached an estimated 9.5 billion cubic meters in 2023. This represents a 23% increase compared to 2022. The transport sector consumption of biomethane accounted for 44% of global demand in 2023. Potential applications of biomethane include injection into existing natural gas pipelines for domestic and commercial use, as a fuel for industrial processes, vehicle fuel, and production of green hydrogen. Methane can be upgraded by mixing it with hydrogen to produce more potent fuel, which can be used in transport and other commercial applications. In the method of producing methane from renewable energy, the generated electricity is used to electrolyze water and produce hydrogen, which is blended with methane to produce a fuel mix. This route permits storing surplus renewable-based electricity in enriched methane form and hence mitigates the intermittency of renewable energy resources and alleviates the electricity grid load. Considering the projected future production of biomethane and fields of application, its contribution to decarbonizing this fuel sector will be significant.

3.3 Biohydrogen

Currently, increasing efforts are ongoing to produce biohydrogen from organic wastes in order to reduce dependence on petroleum-based hydrogen. The developed processes of biohydrogen production include biofermentation, biophotolysis, and bioelectrochemical systems. Biofermentation is a biological process used to produce biohydrogen, where microorganisms convert organic matter into biohydrogen. This process can be achieved through dark fermentation or photo-fermentation. Dark fermentation is characterized as a fermentation process without the need for light. This process uses anaerobic bacteria and various organic substrates such as glucose, cellulose, or biomass.

Photo-fermentation is a biological process where photosynthetic microorganisms use light energy to convert organic matter into biohydrogen and carbon dioxide. This process offers a pathway for sustainable biohydrogen production, especially when using waste materials as a substrate. Combining photo-fermentation with other processes like dark fermentation can improve biohydrogen output.

Biophotolysis is the process where light is used by biological systems, specifically algae and cyanobacteria, to break down water into hydrogen and oxygen. This process utilizes solar energy to drive the conversion of water into these two gases. Direct and indirect biophotolysis use sunlight to produce biohydrogen. Direct biophotolysis uses solar energy to split water into hydrogen and oxygen. Indirect biophotolysis uses light to create carbohydrates from carbon dioxide, which are then fermented to produce biohydrogen. A bioelectrochemical system utilizes microorganisms to convert organic matter into biohydrogen through electrochemical reactions.

Although, in 2023, the global hydrogen production reached 97 million tons, with a small percentage being low-emissions hydrogen, the search results indicate that biohydrogen is a fast-developing market with production focused on various feedstocks and technologies. Figure 8 shows the biological biohydrogen production processes.

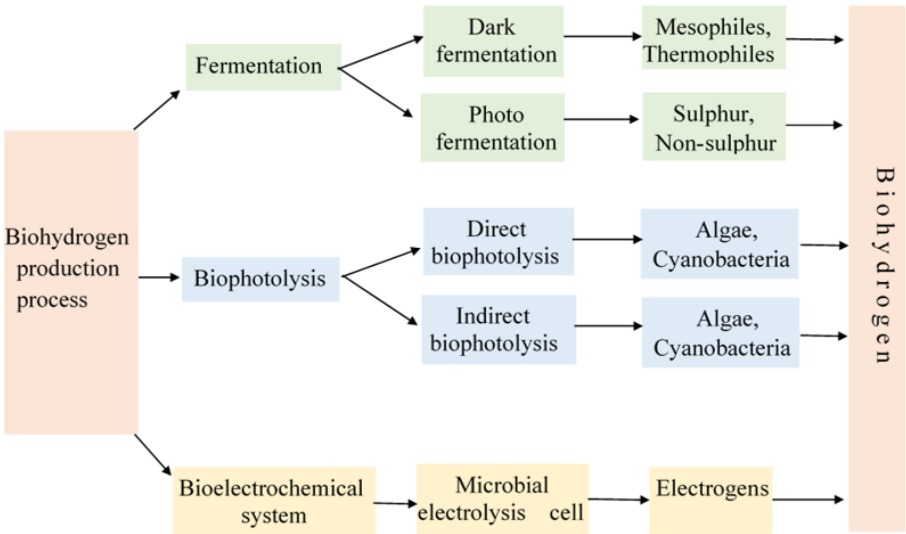

Figure 8. Overview of the biological biohydrogen production processes, adapted from the study [61]

The technology for biohydrogen production is still less competitive. Various low-cost materials, like domestic organic waste, activated waste sludge, etc., can be used as feedstocks to produce biohydrogen through different biological processes. Biohydrogen production from organic materials faces challenges such as reducing costs, addressing environmental concerns, and increasing production efficiency. Different studies were destined for the treatment of diverse aspects of biohydrogen production from organic waste, including processing conditions, bioprocessing strategies, and other economic issues.

Biohydrogen can be obtained from organic waste and also from wastewater from industries. Different biological technologies are available and can be used to produce biohydrogen from these waste materials [62]. Yun et al. [63] reviewed the utilization of FW to produce biohydrogen by dark fermentation and presented some enhancement strategies, challenges, and limitations besides research and future perspectives. Jarunglumlert et al. [64] presented an up-to-date evaluation of biohydrogen production, challenges, and enhanced production strategies, besides a feasibility analysis of large-scale production.

Bio-hydrogen can be produced by different biological processes, but the dark fermentation method of production is receiving more attention due to the low energy used and the higher hydrogen production rate [65, 66]. Melikoglu [67], Saravanan et al. [68], and Malode et al. [69] presented reviews of FW reutilization techniques to reduce environmental impacts and generate jobs and income, investigating biohydrogen production, techniques and barriers, and enhancement strategies.

On a global level, a huge amount of food is wasted annually, and therefore its recovery can protect the environment, reduce emissions, and produce energy. Food residue viability as material to be used to produce biohydrogen was addressed by different authors, including Habashy et al. [70], Lepage et al. [71], and Saravanan et al. [72], who investigated the different methods used to convert biomass to biohydrogen, the merits, challenges, limiting barriers, and recent advances. Xu et al. [73] reviewed the technologies associated with biohydrogen production and highlighted the energy benefits and the environmental gains from using agriculture and FW. Karayel et al. [74] mapped the Turkish regions in function of their potential of biomass used for biohydrogen production. The result shows that the total potential for biohydrogen production using the available sources of biomass in Turkey is around 1.66 million tons/year.

Tamaian et al. [75] investigated the use of food residues to produce biohydrogen by dark fermentation and photosynthesis. Sahota et al. [76] presented a review on technical and research investigations done on the utilization of FWs for producing biogas and biohydrogen. The objectives included the enhancement of energy yield, impacts on the environment, and the financial gains. Melikoglu and Tekin [77] conducted a study on biohydrogen generation potential from wheat, maize, rice, and potatoes; associated losses; and household FW generation in Turkey till 2030. An estimate of about 90,000 tons of biohydrogen could be produced, which represents a potential gain from biohydrogen production.

Tleubergenova et al. [78] explored the potential of biomass-to-biohydrogen production, including the availability and quality of biomass resources and environmental sustainability. The total amount of biohydrogen production from agricultural waste was 432 tons/(km^2/year). Pachaiappan et al. [79] reviewed recent developments in biohydrogen production and discussed their merits and drawbacks and the effects of the influencing factors. The authors showed the latest research and commercial trends and gaps. Ivanenko et al. [80] and Rathi et al. [81] reviewed the basic principles of the main light-dependent and light-independent methods of biohydrogen production, the advantages and disadvantages of these methods, and other strategies for improving biohydrogen production. Production methods, benefits and drawbacks, and affecting variables have been investigated. Daş et al. [82] presented a review of the different wastes to biohydrogen and/or biogas technologies via fermentation from the perspective of life cycle analysis and commented that the integration of biohydrogen production and anaerobic digestion from organic wastes could be an attractive production option. Akram et al. [83] commented on the remarkable qualities of hydrogen as a future energy carrier and highlighted various biohydrogen production methods and the challenges to be addressed. Goria et al. [84] presented a study to illustrate the algal biohydrogen production, the barriers, and the economic and technical challenges. Jaradat et al. [85] provided a review on the technological advancements, policy support, international cooperation, and incentives to promote hydrogen. Also, they highlighted the importance of low-cost hydrogen production methods.

Goveas et al. [86] presented a review showing the need for novel techniques such as genetic engineering to improve hydrogen yield and discussed the prospects for future commercial use. Machhirake et al. [87] presented a review on the role of biohydrogen recovered from waste biomass and sewage sludge as a promising solution. The biochemical technologies and methods for producing biohydrogen were overviewed. Future research and investment, as well as potential problems, economic impediments, and policy-related issues, were discussed. Eloffy et al. [88] reviewed the processes for biohydrogen production from biomass, such as thermochemical, biological, and electrochemical, and the optimization of the different parameters, and discussed the advancements and technical challenges.

Merabet et al. [89] presented a review on the feasibility of hydrogen production from wastewater and reported on the limitations, challenges, techno-economic assessments, future directions of research, and industrial implementation. Kundu et al. [90] discussed the various processes, including thermochemical, biological, and electrochemical conversions, coupled with modified pretreatment methods to enhance the yield of biohydrogen production, and provided a critical analysis of diverse developed processes.

Chen et al. [91] addressed the problems in biohydrogen production, such as hydrogen-producing organisms and production systems. It is concluded that coupling hydrogen production with organic waste treatment and multi-type combination is an economically feasible way for biohydrogen production. Irawan et al. [92] examined biohydrogen's potential, focusing on the dark fermentation process, and suggested the integration of biohydrogen production within the agricultural system. Ananthi et al. [93] reviewed several technologies, including photolysis, photo fermentation, and dark fermentation, for potential biohydrogen production from lignocellulosic biomasses and commented that practical difficulties and limitations could be overcome by integrating fermentation approaches with metabolic engineering practices. Meena et al. [94] focused their study on utilizing lignocellulosic biomass and FW as substrates and pretreatment methods to enhance biohydrogen yield. Results showed improvements in biohydrogen yield. Rey et al. [95] reviewed and compared existing biomass-to-hydrogen technologies, focusing on their characteristics, maturity level, benefits, limitations, and techno-economics. The authors commented that thermochemical processes suit centralized large-scale hydrogen production, while biological processes offer decentralized options and need more research and development.

Remarks

Hydrogen, or biohydrogen, is considered the fuel of the future since it is clean and can be produced from water and organic sources. The market for its use is wide and in expansion. In 2023, global hydrogen demand achieved 97 million tons, with about a 2.5% increase compared to 2022. The majority of this demand was met by fossil-based hydrogen, where the low-emissions hydrogen accounted for less than 1 million tons of this total demand. Hydrogen consumption is currently concentrated in industrial sectors like refining and ammonia production, but its use is expanding into other areas like transport, power generation, the aerospace industry, the glass industry, and energy storage [96].

4 Liquid Biofuels from Organic Wastes

Exploring the different energy forms and utilization always accompanied the progress and development of humans over centuries. Fossil fuels and biofuels equally participated in the process but suffered changes imposed by the global political and economic interests. For a very long time, while progress in biofuels was stagnant, fossil fuels assumed the lead in transport, electricity generation, and other aspects. Global environmental changes caused by the excessive use of fossil fuels and the continuous growing need for energy and fuels urged the search for alternatives adequate in form and quantities to replace fossil sources. In recent decades, biofuels, including bioethanol, biodiesel, and biohydrogen, have shown considerable promise as alternative options for future transportation fuel needs. The primary biofuels require no processing and are used directly for cooking, generation of steam for transport, etc., while the secondary biofuels are regarded as processed biofuels and are proposed to handle the different forms of energy needs and utilization, such as transport and electricity generation, among others (Figure 9).

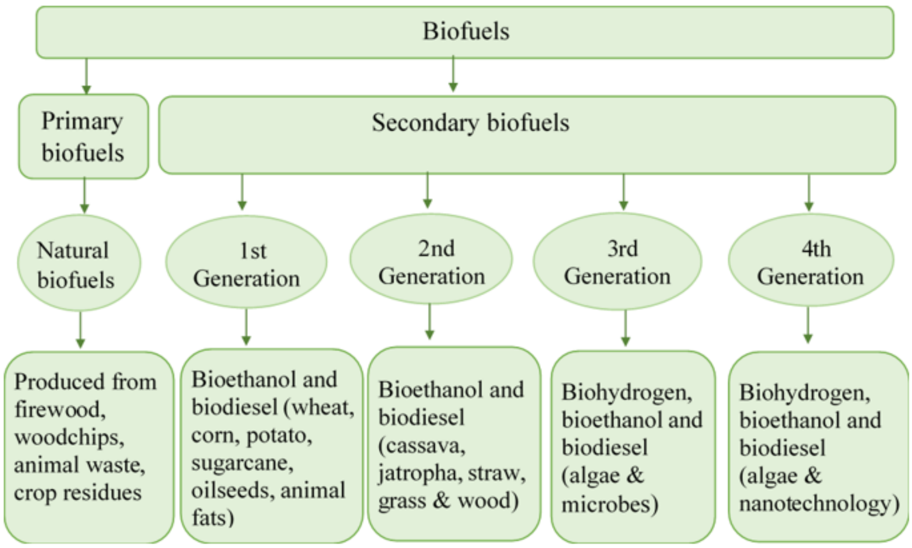

Figure 9. Evolution of biofuels adapted from the study [97]

4.1 Bioethanol

Management of agriculture crops usually results in residues that are left on-site or used to generate heat and electricity. Agricultural crops were used replace fossil-based fuels as feedstock for generating bioethanol from sugarcane and sugar beet, while biodiesel can be produced from soybeans and other vegetable oils. Figure 10 shows a simplified line diagram of the bioethanol production from sugarcane. 1G bioethanol produced from agriculture crops causes great concerns relative to interference with food supplies and land use. These concerns urged the search for alternate feedstock for producing bioethanol, and agricultural wastes appeared as good solutions. This gave rise to 2G bioethanol from sugarcane bagasse. In this case, the carbohydrates in the bagasse are converted into fermentable sugars and then to bioethanol. Furthermore, research and developments showed that bioethanol can be produced from residues of maize, wheat, and cellulosic biomass. Figure 11 shows a simplified line diagram of the main steps of processing biomass wastes to produce bioethanol.

Bioethanol can be produced from agricultural waste, but its economical production is constrained by the transportation and handling of biomass, the effectiveness of pretreatment for delignification of lignocellulosic substrates, enzymatic hydrolysis, and the availability of suitable fermentative organisms, among others. Research

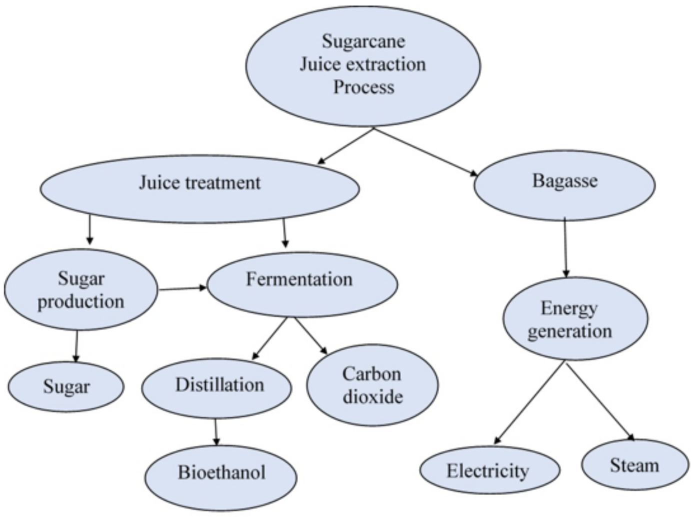

Figure 10. Processes for sugar and bioethanol production from sugarcane, adapted from the study [98]

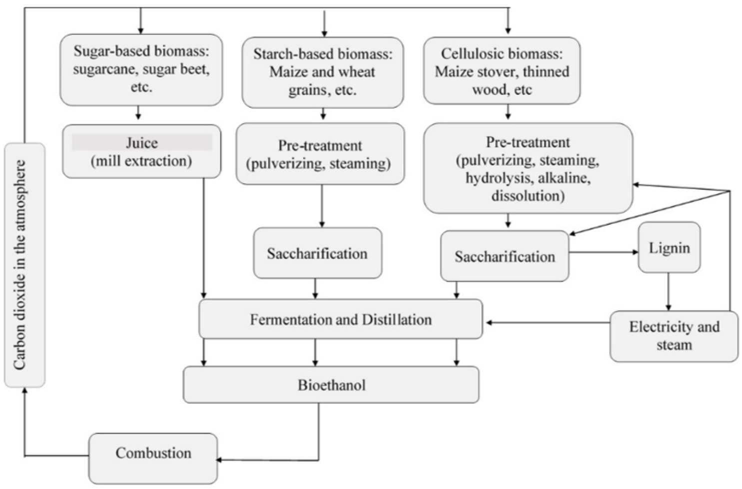

Figure 11. Diagram of processing biomass wastes to produce bioethanol, adapted from the study [99]

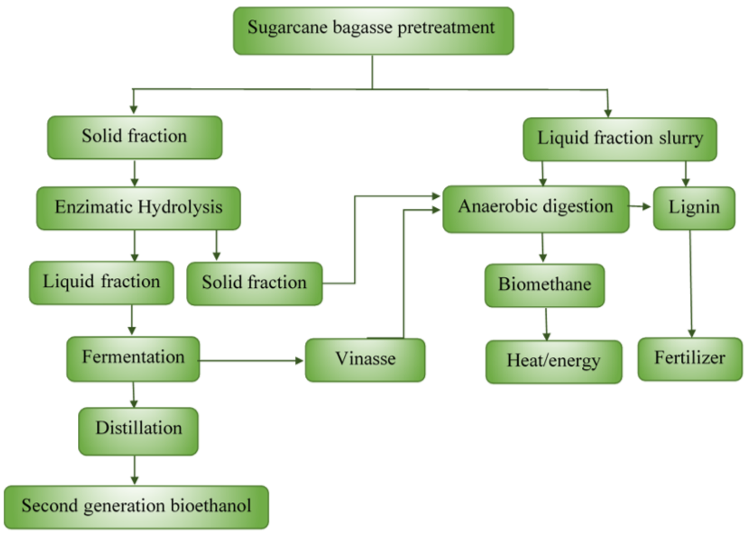

Figure 12. Integrated processes for bioethanol 2G and biomethane production, adapted from the study [100]

results showed that lignocellulose feedstocks are promising sources for 2G bioethanol. Figure 12 shows the integrated processes for 2G bioethanol and methane produced from sugarcane bagasse.

Tse et al. [101] presented a review whose main purpose is to provide industrial producers and policy makers insight into available technologies, yields of bioethanol achieved by current manufacturing practices, and goals for future innovation. The authors compared bioethanol production from a range of feedstocks and discussed the available technologies, including fermentation. Mgeni et al. [102] conducted a review to evaluate the potential of fruit waste for bioethanol production. Various techniques, including enzymatic hydrolysis, fermentation, and distillation, were addressed, and challenges such as seasonal availability and substrate variability were reviewed.

Malik et al. [11] presented a review on the use of the agricultural residues to produce bioethanol via hydrolysis and fermentation. Several agricultural residues, pretreatment techniques, hydrolysis and fermentation techniques, challenges, and future perspectives were discussed.

Samantaray et al. [103] presented a review of agricultural wastes, pretreatment techniques used for the delignification of waste biomass, and fermentation techniques used for the conversion to bioethanol. Further, the integration of various modern techniques has also been highlighted for enhanced bioethanol production.

Owusu et al. [104] reviewed the utilization of Sargassum to produce bioethanol. Ghana produces bioethanol from edible crops and biomass of high lignin content. The authors investigated the availability of sargassum, chemical composition, processes, and opportunities for bioethanol production. Bibra et al. [105] presented a review focused on the opportunities and challenges for using the FW, the fermentation process, and improvement of the process economics. The impact of substrate and by-product stream was also discussed. Mazhar et al. [106] provided a review to explore alternative techniques for generating biofuels that are less time-consuming, sustainable, and eco-friendly.

The utilization of FW to produce ethanol helps to dispose of these organic wastes correctly and reduces emissions. The composition of organic FW makes it valuable to generate biofuels through various fermentation processes [107]. Hafid et al. [108] presented a review of domestic cooking wastes and their use as substrates for bioethanol production. Pretreatment by physical, chemical, and biological methods, the merits and drawbacks, and limiting barriers and challenges were discussed. The use of FW to produce ethanol by sustainable processes was investigated by Saeed et al. [109] with a special focus on the full utilization of FW and cost reduction, besides enhancing the fermentation process, while Dhiman and Mukherjee [110] investigated the characteristics of FW, its management, its use for biofuel production, and future scope and challenges. Panahi et al. [111] reviewed the FW, pretreatment methods, and the barriers for its use to produce bioethanol and biodiesel for the transport industry.

Van Rooyen et al. [112] evaluated thermal and chemical decontamination strategies for pre- and post-consumer FW. Results show that thermal sterilization at an elevated liquefaction temperature significantly improved ethanol. Anaerobic bioconversion integrated with pyrolysis is a promising solution for FW management and energy production but still faces some challenges [113]. Hamdi et al. [114] reviewed the ways of converting agricultural and fruit waste into bioethanol and highlighted their benefits, pretreatment, and control of pH and temperatures [115].

Remarks

In 2023, global fuel ethanol production reached a record 29.5 billion gallons. The United States produced 15.58 billion gallons, representing 52% of the world's total, while Brazil produced 8.47 billion gallons, or 28% of global production [8].

The composition of organic FW makes them valuable to produce biofuels such as biogas, bioethanol, and biodiesel through various fermentation processes. This helps to dispose of these organic wastes correctly and reduces emissions.

4.2 Biodiesel

Agriculture and food production industries generate tremendous amounts of organic waste worldwide. As was mentioned, research results have shown that these organic wastes can be used for producing a variety of biofuels using available technologies. These adopted conversion routes do not threaten food supplies or food security but solve the waste management problems.

Transesterification, a process used in the production of biodiesel, is a reaction to convert fatty and oily feedstock into biodiesel and glycerol. The transesterification using acid catalysis is used for feedstocks with high free fatty acid content, where the acid catalyst converts fatty acids into biodiesel. The enzymatic transesterification offers an environmentally friendly approach, especially when dealing with complex feedstocks or lower-quality oils. Other methods include supercritical methanol transesterification, pyrolysis, and micro-emulsion. Supercritical transesterification uses high temperature and pressure to facilitate the reaction. Pyrolysis involves heating the feedstock at high temperatures (250–350°C) to break down the fats and oils into simpler molecules, some of which can be used as biodiesel. In the case of microemulsion, a stable mixture of oil, alcohol, and a surfactant is created, allowing for easier reaction and potentially reducing the need for catalysts.

Transesterification is the most preferred technique for producing biodiesel irrespective of its sensitivity to water and free fatty acid, but the choice of feedstock can impact both efficiency and biodiesel quality [116]. Figure 13 shows a line diagram of the transesterification route to produce biodiesel with glycerol as a byproduct.

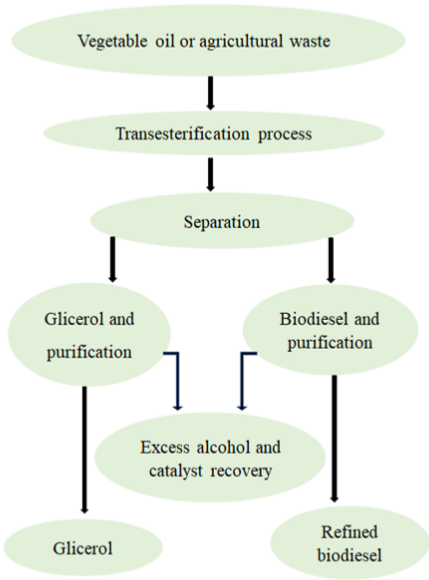

Figure 13. Transesterification process, adapted from the study [117]

Pyrolysis offers a straightforward method for biodiesel production with minimal waste. However, despite its direct applicability, concerns arise regarding the quality of the biodiesel, high energy input requirements, and issues related to fuel stability and combustion efficiency [116].

Karmee [118] commented that the composition of agriculture and FWs facilitates its conversion to a variety of biofuels. The authors discussed the conversion methods used, feasibility, prospects, limitations, and future research opportunities. Demirbas et al. [119] provided a review on plant oils as feedstock to produce biodiesel, characteristics, methods of conversion, and perspectives.

Chhetri et al. [120] evaluated experimentally the utilization of used oil and mixtures of different used oils to produce biodiesel and investigated the effects of the different operational parameters on the quality of the resulting biodiesel. The product was characterized and showed good results as fuel for substituting fossil-based diesel fuel. Banković-Ilić et al. [121] reviewed the techniques for the use of waste animal fats, methods of treatment, the effects of the operation, and the different parameters on the enhancement of the biodiesel conversion process. Cordero-Ravelo and Schallenberg-Rodriguez [122] investigated different waste cooking oils to produce biodiesel. The quality of the resulting biodiesel depends on the type of oil used, and the transesterification method is recommended for producing biodiesel from cooking oils and their mixtures.

Sharma et al. [123] evaluated the properties and chemical characteristics of six waste cooking oils to use to produce biodiesel. Biochemical composition and the characteristics of the produced biodiesel demonstrated that these used oils could be good candidates for biodiesel production but require further investigation of efficiency and emissions. Suzihaque et al. [124] examined used oil as a raw material to produce biodiesel, investigated the various variables of the transesterification method, and compared the waste cooking oil biodiesel with the petroleum diesel. Brahma et al. [125] reviewed used oils, their mixtures, and the effects of the mix ratio on the process rate, productivity, and economic feasibility. Al Azad et al. [126] investigated the fish wastes as a feedstock to produce biodiesel and commented that saturated fatty acids (SFA) increase viscosity, cetane number, and density. The authors concluded that the fish waste has high potential to produce biodiesel with improved properties by transesterification. Babu et al. [127] presented a review of AGW management technologies, advances, efficiency, environmental impacts, and potential. The results and conclusions of the study can help achieve a green economy in the agricultural sector. Cerón Ferrusca et al. [128] and Monika et al. [129] reviewed the lipidic feedstocks, homogeneous and heterogeneous catalysts, characteristics of used cooking oils, and the transesterification-influencing parameters to produce biodiesel. The authors highlighted the challenges in catalyst development for low-grade raw material use to produce biodiesel and the sustainability of the process. Ahmed and Huddersman [130] mentioned that brown grease obtained from trapped waste is rich in fats, oils, and greases (FOGs) and can be used for biodiesel production. The authors reviewed the effects of pretreatment and process parameters on the conversion of FOGs to biodiesel.

The utilization of AGWs to produce ethanol and biodiesel is implemented for various organic wastes but is still in the development stage in the case of biohydrogen. However, Awogbemi and Von Kallon [43] commented that routes are viable and can help achieve the global energy targets. Dhiman and Mukherjee [131] reviewed the current technologies used for producing biofuels from FWs and their effectiveness in reducing the emissions. Azadbakht et al. [132] conducted a study to use AGWs and fats to produce biodiesel. To achieve these objectives, some initiatives need to be provided, including technical, financial, and public policy issues, besides public acceptance.

Al-Muhtaseb et al. [133] evaluated the viability of AGWs to produce biofuels and available methods to convert these wastes to biofuel. The authors concluded that non-edible AGWs are viable options, while the thermochemical methods are preferred because the yield and quality of the produced biofuel are high. Guddaraddi et al. [134] reviewed the use of AGWs to produce biofuel and indicated that this can contribute to solving the global energy problem. The authors evaluated these AGWs as feedstock, their worldwide availability, and their potential yield. The authors commented on the benefits, challenges and barriers, public policies pro-farming, and incentives for research and development. Jamil et al. [135] provided a review on the concepts for converting biomass to biofuels, their contribution to the green economy, and the strengths and weaknesses of the different thermochemical conversion techniques.

Phiri et al. [136] provided an overview of AGW, offering insights into its generation, categorization, and composition and associated environmental implications. Additionally, the review examined managing and utilizing AGWs, addressing challenges such as the waste sources, compositional variations, contaminants, and practical feasibility, and recommended further research and infrastructure development. Kumar et al. [137] commented on the benefits of agricultural lignocellulosic waste, such as cost and quantity. The authors concluded that the major obstacle to using the agricultural lignocellulosic waste is the access to the adequate conversion technology.

Julkipli et al. [138] reviewed the FW and the associated processes to produce biodiesel and hydrogen besides hydrolysis and the composition of FW. Hydrogen production is done by dark fermentation and photo fermentation, while biodiesel is produced from lipid-rich biomass from FW by transesterification. Mekunye and Makinde [139] and Zielińska and Bułkowska [140] presented reviews on the utilization of AGWs for producing biofuels such as biomethane, biohydrogen, and biodiesel by available methods. The review covered types of lignocellulosic biomass, composition, conversion techniques, and challenges. Borthakur [141] provided a review on utilizing agricultural residues for biodiesel synthesis, the technological advancements, and socioeconomic benefits, besides addressing challenges like feedstock variability and collection logistics. Suhara et al. [142] provided a review of sustainable biofuel technologies, advancements, the challenges and opportunities, availability of feedstock, supporting policies, and stability of prices. Quevedo-Amador et al. [143] reviewed organic waste-based solid catalysts, advances in biofuel production, their advantages and drawbacks, and future research trends. Tulashie et al. [144] reviewed the recent advancements in the production of biodiesel from used oils, focusing on feedstock selection, conversion technologies, and the environmental and economic viability. Chia et al. [145] provided a review on the potential feedstock for biodiesel production in Malaysia and commented that more investigation and studies are required to compromise high cost and technology immaturity.

Ghosh et al. [146] proposed an integrated reactor design for the heterogeneous catalytic transesterification process for biodiesel production to enhance commercial productivity and economic viability. The authors discussed biodiesel production methods, efficiency and limitations of heterogeneous catalysts, as well as challenges and future outlooks.

Pranta and Cho [147] summarized the recent developments in advanced biodiesel synthesis techniques, evaluating various catalysts, including homogeneous, heterogeneous, biocatalysts, nanocatalysts, and ionic liquids, alongside factors such as feedstock generations, lipid content, and operating conditions affecting biodiesel yield. The study also analyzed various uncertainty methods and emphasizes the importance of continued innovation.

Glycerol is a byproduct of biodiesel fabrication and accounts for about 10% of the total production. The volume of glycerol produced is increasing continuously due to the worldwide increase of biodiesel production, achieving 71.5 million tons in 2023. Since the existing glycerol supply and demand market is balanced and cannot absorb the additional generated glycerol, the development of new applications for the additional glycerol is necessary to enhance the biodiesel industry [148]. Table 1 shows the glycerol properties.

The crude glycerol purification process using a physiochemical route is shown in Figure 14, adapted from the study [148].

Konstantinović et al. [149] reviewed glycerol, methods of production and purification, uses of glycerol as a green solvent, and possible value-added products, including biofuels. Bateni et al. [150] reviewed the processes of purification and upgrading applied to biodiesel to improve its moisture absorption, corrosiveness, and high viscosity, which are addressed by several upgrading techniques, including catalytic deoxygenation using conventional hydrotreating catalysts. Rodrigues et al. [151] and Almeida et al. [152] investigated producing biohydrogen by co-biodigestion of crude glycerol and sanitary sewage. The results were promising, indicating one more relevant application of glycerol. Organic and oily wastes are feedstock utilized to produce biodiesel and can also be used to produce jet biofuels, which can help decarbonize the aviation sector.

Ningaraju et al. [153] proposed purification of biodiesel by an acidification process and obtention of $\mathrm{Na_2SO_4}$ and $\mathrm{K_2SO_4}$. The results reveal that the process is promising and produces glycerol with about 95% purity. Elsayed

Table 1. Properties of glycerol at room temperature [148]

Property	Value
Molar mass ($g \cdot mol^{-1}$)	92.094
Appearance	Colorless hygroscopic liquid
Odor	Odorless
Density ($g \cdot cm^{-3}$)	1.261
Melting temperature (℃)	17.8
Boiling temperature (℃)	290
Lower heating value ($MJ \cdot kg^{-1}$)	24
Refractive index	1.4746
Viscosity ($Pa \cdot s$)	1.412

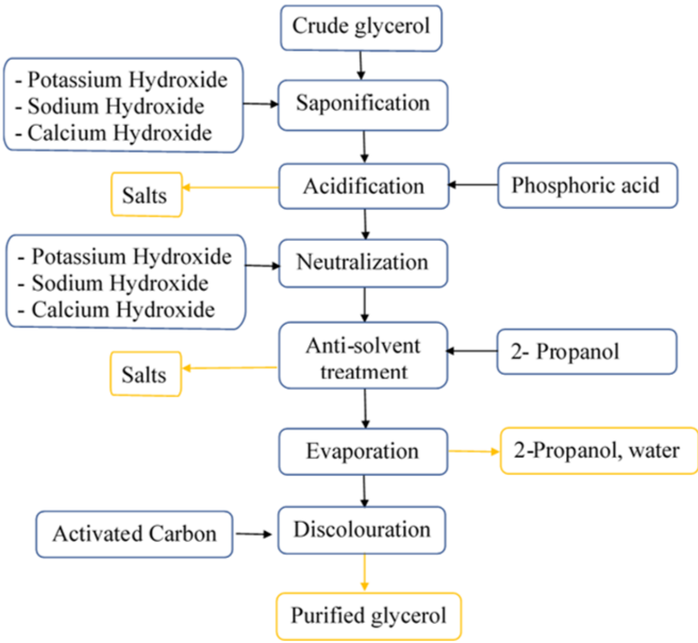

Figure 14. Crude glycerol purification process using a physiochemical route adapted from the study [148]

et al. [154] reviewed crude glycerol and highlighted its composition. Waste glycerol from the biodiesel industry represents a challenge. To address the challenge of waste glycerol, further research and development are required. Tomatis et al. [155] assessed the environmental impacts of crude glycerol purification, which is of great interest to the biodiesel industry. Babadi et al. [156] discussed the advances, opportunities, and future perspectives in biodiesel production technologies, while their limitations and challenges are critically explained. The study focused on a variety of established catalytic technologies as well as the potential of emerging technologies and their future prospects. The current challenges of conventional technologies and new alternative techniques were discussed. Bansod et al. [157] presented a comprehensive techno-economic assessment of three glycerol purification processes. Ion exchange purification achieved the highest glycerol purity, while vacuum distillation showed the lowest capital cost.

Remarks

Global biodiesel production reached a record high of 71.5 million tons in 2023 and is projected to reach 76.3 million tons in 2024, a 7% increase. The production is estimated to increase to attend to the transport sector. To avoid conflicts with the food supplies, urgent research and development are required to use organic waste for this additional biodiesel.

Biodiesel production from agricultural and FW continues to be an area of active research and development, focusing on using waste streams like cooking oils, animal fats, and plant residues to create biofuel that competes with conventional diesel. More research is required to reduce costs of production and ambient impacts.

Glycerol is a by-product of the biodiesel industry, accounting for about 10% of the production. Considering the increasing tendencies of biodiesel production, new possible applications to valorize glycerol are needed. Among the possible applications, its use to produce bioethanol and biohydrogen are both highlighted as viable solutions.

4.3 Jet Biofuel

Aviation is a sector that contributes much to the global emissions and is by far the sector most retarded in relation to the transition to renewable biofuels. Estimates show a strong global increase of emissions in the next few decades if no action is taken to limit or reduce aviation emissions. As shown in Figure 15, between 1980 and 2020, global CO_2 emissions from civil aviation increased from approximately 400 million tons to over 1000 million tons, with a notable increase after 2000 [158–161]. Aviation is responsible for 13.9% of transport emissions, and according to the report [96, 162], in 2023 aviation CO_2 emissions achieved about 950 million tons CO_2, more than 90% of pre-Covid-19 levels, and it is forecasted that by 2050 aviation emissions could increase three times in comparison with those of 2015.

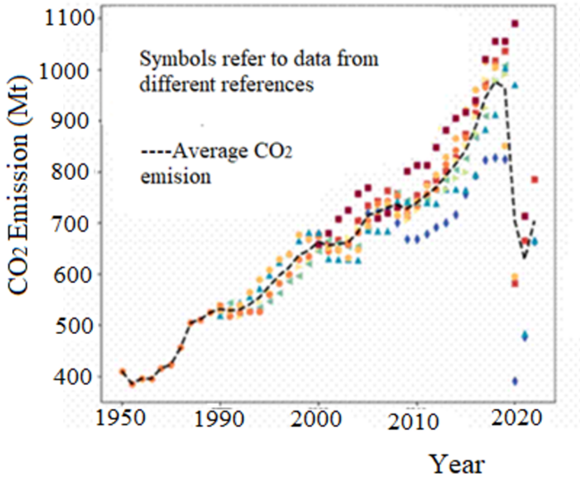

Figure 15. Evolution of aviation CO_2 emissions over time, adapted from the review [161]

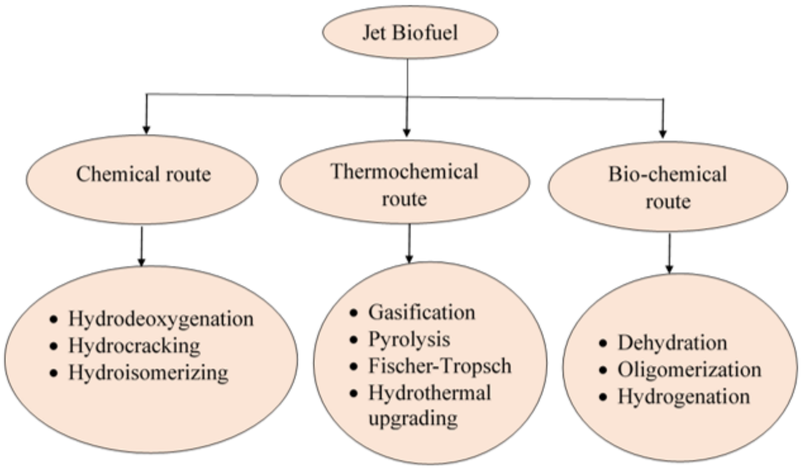

Figure 16. Jet biofuel production routes, adapted from the study [163]

A worldwide shift towards environmentally friendly renewable fuels is necessary to mitigate the environmental impacts of aviation fossil fuel. There are various biomasses, such as sugar, lignocellulosic, starchy, triglycerides, etc., that can be utilized for jet biofuel production through chemical, thermochemical, and biochemical conversions, as shown in Figure 16. Research and development are going on, covering different fronts, including modeling, optimization of the presses, availability of feedstock, thermal and chemical stability of jet biofuel with time, performance tests, safety, and attending to regulations of the aviation sector, besides cost and production infrastructure.

The production of sustainable aviation fuel (SAF), which is composed of biofuel obtained from renewable sources like waste oils, fats, and plant-based materials and blended with conventional jet fuel, reached 600 million liters in 2023, doubling the production of the previous year and representing 0.53% of the total global jet fuel demand.

Yilmaz and Atmanli [164] investigated types of biofuels for aviation, feedstock availability, production costs, and possible technical and operational challenges. Neuling and Kaltschmitt [165] presented a brief overview of biokerosene from vegetable oil technologies and the production processes, besides identifying several barriers and further research and development opportunities.

The effects of jet biofuel thermal and chemical properties on its performance, conversion technologies, economic issues, and search for viable feedstock and the technical barriers for further improvements were reviewed by Yang et al. [166], Why et al. [167], and Wei et al. [168]. Shahabuddin et al. [169] reviewed jet biofuel from biomass and AGW and commented that efficiency and capital costs are strong challenges for its worldwide spread by the aviation industries. Goh et al. [170] presented a review showing that used oil can be used to produce biofuel for ground and aviation industries. Doliente et al. [171] and Gollakota et al. [172] addressed different aspects of the jet biofuel, including availability of feedstock, methods of production, possible upgrading challenges, transport and storage, and competitiveness. Alherbawi et al. [173] reviewed the hydroprocessing of Jatropha, including performance, availability of feedstock, and price competitiveness. The results showed that production by hydroprocessing can achieve a 75% reduction in emissions compared to conventional jet fuel.

Zhang et al. [174] evaluated the organic wastes as feedstock to produce aviation fuel through thermochemical methods. The review showed significant variation of the yield and quality of these fuels. The authors recommended more investigation to enhance the aviation fuel from these organic wastes. Ahmed et al. [163] discussed the recent technologies to produce jet biofuel, the type of feedstock, and its availability, sustainability, competitiveness, and environmental impacts.

Different feedstock and biomass wastes are currently being investigated to produce jet biofuel. Emmanouilidou et al. [175] evaluated the utilization of organic and AGWs to produce jet biofuel by using current conversion methods. It was shown that there is a need for more research and development to achieve secure results. Saurabh [176] commented that jet biofuel is less offensive to the environment and has a high energy density, which results in better fuel economy. Watson et al. [177] presented a review assessing the sustainable jet biofuel technologies, their costs, emissions, policies, and market and highlighted the jet biofuels' low-carbon emission in comparison with traditional jet fuel. Zhang et al. [178] commented that producing jet biofuel from biomass and biowastes can help decarbonize the aviation sector. The authors discussed the available conversion techniques and operational conditions, including challenges and possible future research. Mansy et al. [179] reviewed the recent techniques to produce jet biofuel from biomass and commented that the utilization of jet biofuels in the global aviation industry can produce a significant decrease in the emissions of the sector.

Remarks

SAF is made from renewable resources like used cooking oil, waste, and plants that can significantly reduce aviation's carbon footprint. It is a "drop-in" fuel that is blended with traditional jet fuel and operates normally with existing aircraft technology and fueling installations. CO_2 released when burnt is much lower than conventional jet fuel.

Regulations currently require it to be blended with traditional jet fuel, typically up to a 50% maximum. It is important to mention that SAF meets the same technical standards as conventional jet fuel, ensuring it is just as safe to use.

The demand for SAF should increase dramatically by 2050 for aviation to achieve the zero net emissions target. Estimates suggest that the SAF may account for about 65% of the required emission reduction, with production needing to increase from 100 million liters to at least 449 billion liters per year. In 2024, SAF made up approximately 0.3% to 0.6% of global jet fuel. SAF prices are higher than conventional jet fuel, with market prices around $2,000–$2,350 per ton in 2024.

It is important to mention that the number of airports regularly supplied with SAF is over 69 airports and that the number of commercial flights operated using SAF since 2011 is more than 904,339 flights.

5 Solid biofuels from Organic Wastes

Solid biofuels have always been present in humans' daily lives since the era in which the humans started to use fire for heating and cooking. Solid biofuels, such as firewood, woodchips, forest trash, etc., are also denominated as primary fuels, require no processing, and are used directly for the generation of heat and electricity. Organic wastes from crops and food processing and leftovers usually have a big volume, which makes them less attractive for use due to transport, handling, and storage issues. The densification of these residues facilitates their commercialization and acceptance for energy use.

To achieve these objectives, two methods are usually used, namely torrefaction and pelletizing. Torrefaction is the heating of biomass at 200–300°C without oxygen to increase its energy density and remove moisture and volatile organic compounds while preserving the carbon content. Upgrading biomass by torrefaction reduces the volume and increases the energy density of biomass and residues besides facilitating their transport and storage and improving their acceptance by the users. Van der Stelt et al. [180], Nhuchhen et al. [181], Poudel et al. [182], and Saravanan et al. [25] showed that the torrefaction temperature increases the higher heating value. The authors also investigated the associated technology, domestic and industrial applications, and economic potential of the torrefied biomass and

FW. Figure 17 shows a simplified line diagram of the torrefaction process.

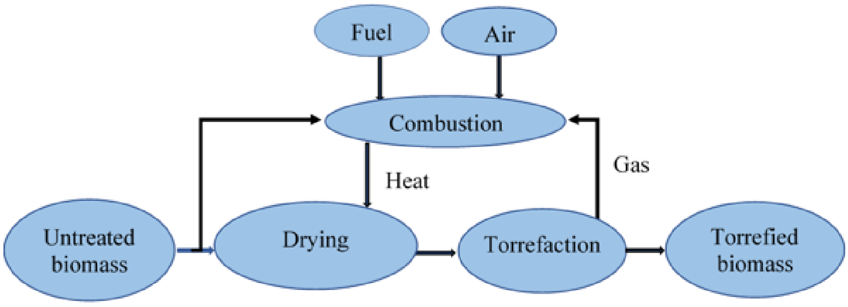

Figure 17. Simplified scheme of the torrefaction process, adapted from the study [183]

In the process of pelletizing or briquetting, the residual biomass is ground and pinned, then placed in a heated press, where a binder or glue is added and then pressed by the piston heating system. In this process, the material can be from a single source or a mixture of biomass to increase the calorific value or reduce the effect of ash. Pellets and briquettes must have good mechanical strength so as not to suffer mechanical damage and should be resistant to moisture absorption.

Chen et al. [184] investigated utilizing organic materials in wastewater to generate biofuels and chemical elements. Bai et al. [185] examined the process of co-pelletization of a mixture of wheat straw and peanut shell under the conditions of 15% peanut shell and 10% water content and determined all characteristics of the resulting biochar. Barskov et al. [186] reviewed the possibilities of torrefaction of food and fibrous agro-residues to produce biocoal.

The temperature and residence duration during the torrefaction of a mixture of food and wood wastes improved the thermal properties of the torrefied product and increased its heating value from 19.15 to 23.9 MJ/kg [187]. The quality and characteristics of the torrefied sugarcane bagasse and the influence of the process parameters on the properties of the product were investigated by Manatura [188]. Cahyanti et al. [189] reviewed the torrefaction of biomass, covering the environmental and economic aspects as well as the quality of the torrefied pellets and their domestic and commercial applications. Olugbade and Ojo [190] reviewed the torrefaction of agro-residues and possible commercial and residential applications, besides investigating the operational mechanisms of the processes. Abdulyekeen et al. [191] assessed the influence of torrefaction on the thermal characteristics of organic wastes and concluded that the effects of the temperature and residence time need to be better studied. Ischia et al. [192] valorized organic solid waste by carbonization for possible biofuel production. The results indicated that hydrothermal carbonization converts the wet waste into a dry solid biofuel while simultaneously extracting biodiesel.

Santana et al. [193] examined the quality improvement that could be produced by using the mixture of lignocellulosic for the production of pellets and the use of forest biomass for pelletizing. Pellets with sugarcane bagasse showed a net heat content of 15.1 MJ/kg, adequate for industrial and commercial applications.

Microwave roasting and pelletizing can improve the fuel properties of biomass and its energy applications, while plastic waste can be used as a binder. The results showed improvements of the thermal and moisture absorbance properties of biofuel pellets [194].

Velusamy et al. [195] evaluated the combustion characteristics of briquettes manufactured from onion peel, tamarind peel, and cassava flour. The briquette of the onion peel–tamarind peel mixture showed better properties as biofuel compared to the briquettes made from organic solid waste. Khan et al. [196] reviewed the hydrothermal carbonization of FW, including the influence of temperature, time, and pressure, among other parameters, on the thermal characteristics of hydrochar.

Sunnu et al. [197] conducted a study to use char and briquettes from various AGWs as biofuels. The results indicated that the palm bark achieved the highest thermal performance, reaching a value of 20.836 kJ/kg. Moreira et al. [198] evaluated the combustion of pellets from wheat straw and cashew shells. The results were favorable with low emissions.

Wu et al. [199] reviewed the recent advances of hydrothermal carbonization and its application for FW to produce hydrochar. Kalak [200] evaluated using the industrial organic waste for energy purposes and confirmed its viability for generation of electricity and heat.

Remarks

Biosolid fuels, considered as a primary energy resource, have always accompanied humans in their daily tasks since the early settlement age. With the continuous development of the society and the scientific and technological advances, it was possible to transform the solid organic matter into pelletized, briquetted, and torrefied forms that are more energy dense and easy to store and use. This helped to valorize and popularize their utilization in domestic and commercial applications, boosting up the local bioeconomy and sustainability.

6 Biorefinery and Biofuels

In biorefineries, by using processes such as thermochemical and biochemical for treating organic material and agricultural and FWs, bioproducts such as biofuels, chemical products, electricity, and heat can be obtained. Through biorefinery, the biomass and the generated wastes are valorized, providing additional gains such as stimulating circular economy, reducing emissions, preserving raw materials, and contributing to ambient sanitation. Figure 18 shows the integrated utilization of the agriculture oil crop to produce biodiesel and 2G biofuels. As can be observed from the flow chart, the raw material is utilized for producing different products, and the residues generated from the different processes are used as feedstock for other processes to produce different products, ending finally with minimal inert rejects.

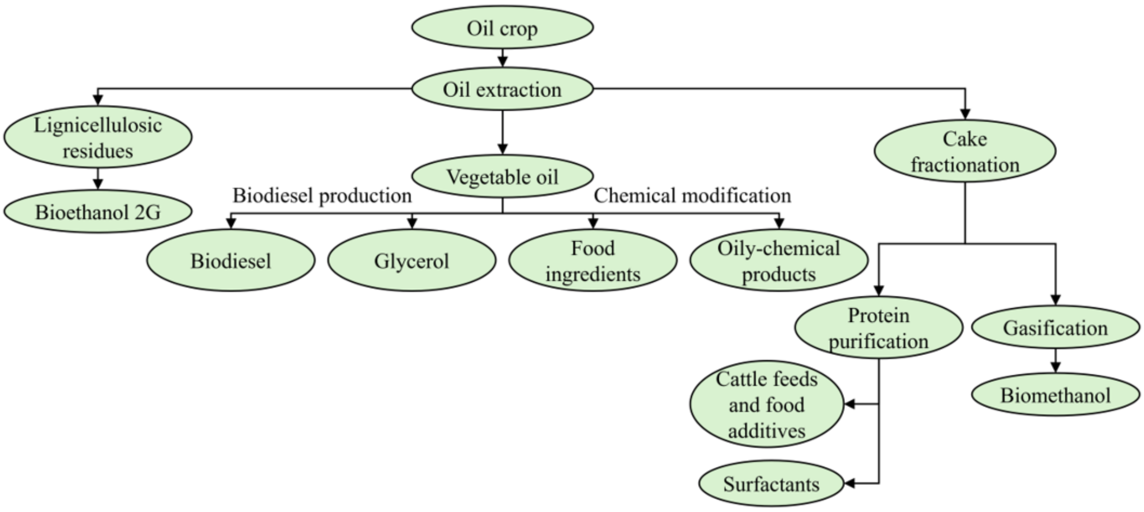

Figure 18. Whole crop biorefinery, adapted from the review [201]

Jin et al. [202] reviewed the phases of the biorefinery concepts, their applications, and advances in the sector, besides the techno-economic, environmental, and social issues. Zhou and Wang [203] reviewed the research on biomass waste and its use in the production of functional materials. Jeevahan et al. [204] reviewed the available technologies to transform organic wastes to useful products and presented a discussion on the advantages, limitations, potential applications, and future perspectives. Sarangi et al. [205] reviewed the application of pineapple waste to produce bioenergy, biochemicals, and other products. The processing of pineapple produces 60% of the original weight in waste that can be used and converted into bioethanol, biohydrogen, and biomethane, as well as animal feed and vermicomposts.

The biorefinery process of using agro-industrial waste not only generates renewable energies but also offers environmentally sustainable ways of managing residues. Yaashikaa et al. [206] presented a review on AGW and using it to produce renewable products besides the sound treatment of AGW. Shah et al. [207] provided a thorough study of the concept and technical advances of biorefinery in waste management and employed the concept for agricultural residues, where biofuels and other chemicals can be manufactured in parallel. The authors also commented on the challenges and future prospects.

Taghizadeh-Alisaraei et al. [208] presented a review on the biorefinery techniques to use AGWs to produce biomaterials, including biofuels. Setyawan et al. [209] presented a review to assess the potential of slurry of biochar fuel from agricultural residues. The production technologies, the characteristics of biochar biomass, and its conversion into slurry fuel were determined and discussed.

The agriculture sector and linked companies annually generate immense amounts of waste, which have great potential to obtain high value-added products in biorefinery processes. Prado-Acebo et al. [210] presented a literature search on integrated biorefinery processes of agro-industrial waste, potential, and feasibility to ensure sustainable development and a circular bioeconomy.

Remarks

In this section, the concept of biorefinery is introduced for the valorization and optimization of the raw material utilized, focusing on the importance of the integration of the technologies for maximizing the gains in the respective production chain. The processing of agricultural edible and non-edible crops and organic wastes is feasible in producing valuable products. The integration of the different methods of producing biofuels via biorefinery allows extracting whatever is useful from processed crops. This integration does not only optimize the production processes but also reduces energy and material losses, enhances the circular economy, and reduces emissions, besides reducing organic waste. However, these achievements need continuous improvements and innovations driven ahead by dedicated scientific research.

7 Conclusions and Future Research Opportunities

7.1 Conclusions

To break off the global warming, it is necessary to change the paradigm related to the generation and consumption of energy. Strategies for mitigation of emissions of GHGs must be based on sustainable energy transition. In this respect, the valorization and the optimized utilization of natural resources, minimizing losses and valorizing and reutilizing wastes, are essential for the production of clean energy. The review shows that the agriculture and food sectors and the associated industries are big producers of organic wastes whose composition is rich in both energy and material.

Dedicated research on using organic wastes to produce biofuels and reduce pressure on food crops, water, and land use resulted in a big expansion of the production of 2G biofuels. Research is continued on algae to produce the third and fourth generations of biofuels, which do not interfere in any aspect with food supply, besides being environmentally friendly.

Research and development continue on using organic wastes for gaseous fuel production via fermentation and other methods to produce biogas, biohydrogen, and biomethane for transport and domestic and commercial applications, while the digested material can be used as a fertilizer. Torrefaction, pelletizing, and briquetting of organic wastes convert them into more energy-dense, coal-like solid fuel, which can enhance their domestic and commercial acceptance for heating and electricity generation.

In summary, this review shows that biofuels will not only impel the energy industry towards a sustainable global energy transition, reducing emissions and conserving natural resources, but also will provide valuable opportunities to reuse organic wastes to produce biofuels and bioproducts via research and technological developments.

7.2 Future Research Opportunities

Biohydrogen production from organic wastes faces challenges such as production efficiency, cost reduction, and environmental concerns. Research gaps include improving fermentation processes, developing efficient pretreatment methods for feedstocks, and enhancing the overall sustainability of the biohydrogen production cycle. Funding, financial incentives, adequate regulations, and public policies are required.

Bioethanol production from organic wastes is advancing. New research and developments include enhancing ethanol yields, reducing byproduct generation, and utilizing novel feedstocks. Funding, international interactions and cooperation, regulations, and adequate public policies are essential.

Glycerol from the biodiesel industry accounts for about 10% of the production. Considering the increasing tendencies of biodiesel production, new possible applications to valorize glycerol are needed. Among the possible applications is its use to produce bioethanol and biohydrogen; both are highlighted as viable solutions. Developments of environmentally friendly methods, pilot production plants, and technical and economic assessments, besides financial incentives and adequate regulations and public policies, are required.

In 2024, SAF accounted for approximately 0.3% to 0.6% of global jet fuel, indicating the need for more production of jet biofuel to achieve zero emissions in the aviation sector by 2050. Possible alternative routes such as alcohol-to-jet (ATJ) and biomass-to-liquid (BTL) should be investigated besides other alternatives. Research and development are ongoing on a global level to produce jet biofuels from organic wastes safe enough for aviation. The search for suitable feedstock, enhancing competitiveness of jet biofuels, and attending to security and emissions challenges are needed for worldwide production. There is a need for coordinated efforts between industrial developments, research, and the aviation sector to produce jet biofuel with enough quantity and quality to help reduce the environmental impacts of the aviation sector.

Investigations are ongoing on the use of the biorefinery for organic wastes to extract chemical elements in parallel to biofuels production. This concept can help in the management of organic wastes, besides other benefits such as enhancing the circular economy, strengthening multifocal beneficiation of agricultural wastes, and reducing organic wastes sent to landfills.

Authors Contributions

Conceptualization, F.A.M.L. and K.A.R.I.; writing—original draft preparation, F.A.M.L.and K.A.R.I. writing—review and editing, F.A.M.L.and K.A.R.I. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of interest

The authors declare no conflict of interest.

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Nomenclature

AGWs	Agriculture wastes
AGW	Agriculture waste
CO_2	Carbon dioxide
FW	Food waste
FWs	Food wastes
GHG	Greenhouse gas
GHGs	Greenhouse gases
H_2S	Hydrogen sulfide
MSW	Municipal solid waste
MW	Micro wave
SAF	Sustainable aviation fuel
SFA	Saturated fatty acids
ATJ	Alcohol-to-jet
BTL	Biomass-to-liquid